Multiplicity Among Young Brown Dwarfs and Very Low Mass Stars*

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ABSTRACT

Characterizing multiplicity in the very low mass (VLM) domain is a topic of much current interest and fundamental importance. Here we report on a near-infrared adaptive optics imaging survey of 31 young brown dwarfs and VLM stars, 28 of which are in the Chamaeleon I star-forming region, using the ESO Very Large Telescope. Our survey is sensitive enough to detect equal mass binaries down to separations of 0.04–0.07″ (∼6–10 AU at 160 pc) and, typically, companions with mass ratios ($q = m_2/m_1$) as low as 0.2 outside of 0.2″ (∼30 AU). We resolve the suspected 0.16″ (∼26 AU) binary ChaHα 2 and present two new binaries, Hn 13 and CHXR 15, with separations of 0.13″ (∼ 20 AU) and 0.30″ (∼ 50 AU) respectively; the latter system is one of the widest VLM systems discovered to date. We do not find companions around the majority

*We dedicate this paper to the memory of our co-author, Eduardo Delgado-Donate, who died in a hiking accident in Tenerife earlier this year.

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of our targets giving an overall binary frequency of 11^{+9}_{-6}%, thus confirming the trend for a lower binary frequency with decreasing mass. By combining our work with previous surveys of VLM objects (VLMOs) in other star forming regions, we arrive at the largest sample of young VLMOs (72) with high angular resolution imaging to date. Its multiplicity fraction is in statistical agreement with that for VLMOs in the field. In addition we note that many field stellar binaries with lower binding energies and/or wider cross sections have survived dynamical evolution and that statistical models suggest tidal disruption by passing stars is unlikely to affect the binary properties of our systems. Thus, we argue that there is no significant evolution of multiplicity with age among brown dwarfs and VLM stars in OB and T associations between a few Myr to several Gyr. Instead, the observations to date suggest that VLM objects are either less likely to be born in fragile multiple systems than solar mass stars or such systems are disrupted very early (within the first couple of Myr).

Subject headings: stars: formation – stars: low-mass, brown dwarfs – stars: luminosity function, mass function – binaries: general – planetary systems

1. Introduction

Over the past decade, hundreds of brown dwarfs (BDs) have been identified in the solar neighborhood and in star-forming regions, yet there is no consensus on their origins. One possibility is that they form like stars, as a result of the turbulent fragmentation and collapse of molecular cloud cores (e.g., Padoan & Nordlund 2004). Another scenario, which has gained popularity in recent years, is that BDs are stellar embryos ejected from multiple proto-stellar systems (Reipurth & Clarke 2001; Bate et al. 2002).

Recent observations have attempted to distinguish among these scenarios, by comparing physical properties of brown dwarfs and very low mass stars (which we refer to together as very low mass objects, or VLMOs, here) with those of solar-mass stars. Numerous studies have shown that many *young* VLMOs exhibit infrared excesses (e.g., Muench et al. 2001; Natta et al. 2002; Jayawardhana et al. 2003a; Scholz et al. 2007) and spectroscopic signatures of accretion (e.g., Jayawardhana et al. 2002, 2003b; Natta et al. 2004; Mohanty et al. 2005), indicative of disks. But both these diagnostics are only sensitive to the innermost

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portions of the disk and therefore cannot test whether BD disks are truncated, as expected in the ejection scenario. Recently, by modeling mid-infrared and millimeter emission, Scholz et al. (2006) found that >25% of Taurus BDs in their sample have disks with radii >10 AU, contrary to predictions of certain ejection simulations, but some truncated disks may be hidden among their non-detections at 1.3mm. The spatial distribution and kinematics of BDs, in comparison with stars, do not provide definitive tests either; ejection models predict velocities comparable to the velocity dispersions of star-forming associations and clusters, i.e., 1-2 km/s (Moraux & Clarke 2005).

In this context, the multiplicity properties of VLMOs –such as frequency, separations, and mass ratios– could be among the most important diagnostics of their origin. In particular, ejection models predict a very low rate of binaries among BDs (<5-8%) and does not favor the formation of many wide (>20 AU) binary systems (e.g., Bate et al. 2002). Direct imaging surveys of (old) field VLMOs have yielded a binary frequency of ∼15% for (apparent) separations a >1 AU, with maximum separations of ≈20 AU (e.g., Bouy et al. 2003; Burgasser et al. 2003). A search for spectroscopic binaries among the field VLMOs add another ∼11% (Basri & Reiners 2006). Open clusters older than ∼100 Myr also appear to lack wide binary brown dwarfs (e.g., Martín et al. 2003; Bouy et al. 2006a). At face value, these findings seem to support the ejection scenario –though typical binary separation may decrease at lower masses even in the turbulent fragmentation model.

However, perhaps somewhat surprisingly, several wide binary VLM systems have been discovered within the past few years. Among them are: 2MASS J1101-7732 (a ≈240 AU) in the ∼2-Myr-old Chamaeleon I star-forming region (Luhman 2004), 2MASS J1207-3932 (a ≈40 AU) in the ∼8-Myr-old TW Hydrae association (Chauvin et al. 2004; Mohanty et al. 2007), DENIS-P J161833-251750 and USCO-160028.4 (a ≈140 and 120 AU, respectively) in the ∼5-Myr-old Upper Scorpius association (Luhman 2005; Bouy et al. 2006b), Oph 162225-240515 (a ≈240 AU) in the ∼1-Myr-old Ophiuchus region (Jayawardhana & Ivanov 2006), and DENIS-J055146.0-443412.2 (a >200 AU) in the field (Billères et al. 2005). 2MASS J1207-3932 and Oph 1622-2405 are especially intriguing because the secondaries have masses approaching the planetary regime.

If wide binaries, such as these six, are common among VLMOs, that would present a critical challenge to ejection models. Recent high angular resolution surveys in Taurus and Upper Scorpious by Kraus et al. (2005, 2006) and Konopacky et al. (2007) have turned up 4 VLM binary systems (all in the Konopacky et al. 2007 sample) that would be considered wide by the ejection model standards. Here we report on an additional effort to constrain the frequency of wide VLM systems in other star forming regions. In particular, we describe a near-infrared adaptive optics imaging survey of 28 VLMOs in Chamaeleon I designed to

investigate whether multiplicity in the VLM regime depends on age.

2. Observations and Data Analysis

Given its proximity (160 pc; Whittet et al. 1997) and youth ($\sim$2 Myr; Luhman 2004), the Chamaeleon I star-forming region is well suited for investigating multiplicity of young VLMOs. We observed 28 targets with spectral types of M5.25–M8 from the recent compilation by Luhman (2004); their membership in Cha I is supported by several diagnostics including proper motion, radial velocity and position on the H-R diagram. Six additional (random) VLM members reported in the census (3 M5.25, 1 M5.5, 1 M5.75, 1 M6) were not observed due to worsening atmospheric conditions. According to Baraffe et al. (1998, 2003) models, our targets span the mass range of $\sim 0.03 - 0.15\,\mathrm{M}_{\odot}$ (Table 1).

We obtained near-infrared $H(1.66\mu m)$- and $K_s(2.16\mu m)$-band images of 26 of these targets with the NAOS-CONICA (NACO, for short) instrument on the 8.2m Yepun unit of the European Southern Observatory's Very Large Telescope on Paranal, Chile over three consecutive nights starting on March 24, 2006. We used the high-resolution lens of NACO, with a pixel scale of 13.26 mas/pix and a field-of-view of $13.6'' \times 13.6''$. For all observations, we utilized the infrared wavefront sensor (WFS) mode N90C10, which directs 90% of the light to the WFS and the rest to CONICA. Targets themselves served as natural guide stars (NGSs) for the WFS. For each target, six 20 second exposures were combined to produce the final image.

Two other Cha I targets, ChaHα2 and ESO559, were observed in service mode between 2005 May–September using the same instrument set up, along with C-41 in Chamaeleon II (see Barrado y Navascués & Jayawardhana 2004), GY 5 in ρ Oph (Greene & Young 1992) and 2MASSW J1207334-393254 in the TW Hydrae association (Gizis 2002). The latter is known to harbor a planetary mass companion at a separation of $\sim$40 AU (Chauvin et al. 2004; Mohanty et al. 2007), and thus served as a cross-check on our sensitivity. These five targets were observed only in the K_s-band, each with a total integration time of 18 minutes. We inspected the final images, reduced in a standard manner using the NACO pipeline software, visually to look for possible companions. In order to determine our ability to detect companions, we also derived contrast sensitivity curves through statistical analysis of the noise in annuli surrounding the central object. Then we calculated the 5-σ detection limit as a function of separation from the primary for each of the targets. More details on the algorithm for deriving these sensitivities are given in Brandeker et al. (2006). We checked the accuracy of the procedure by artificially inserting faint companions into the images at various separations and trying to recover them; the results were consistent.

We converted the contrast sensitivity limits into mass detection limits given the spectral type of the primaries, Luhman et al. (2003) temperature conversion scale and Baraffe et al. (1998, 2003) models for the appropriate age: 2 Myr for Cha I, 1 Myr for ρ Oph and Cha II, and 8 Myr for TW Hydrae.

To search for companions at smaller separations, we carried out point spread function (PSF) subtraction for the Cha I targets from the primary NACO run. To construct a template PSF, we averaged the PSFs of our brightest targets. By varying the combinations of objects used for the template PSF and comparing the results for consistency, we made sure not to include a binary in the template PSF. None of our objects shows a clear signature of a companion after PSF subtraction. For a more quantitative check, we used an approach similar to the procedure suggested by Bouy et al. (2006a): After PSF subtraction, we measured the residual scatter and looked for objects which show excessive noise in the PSF area. Again, none of our objects shows significantly increased noise, defined as 3σ excess above the average.

To probe the adequacy of this test, we inserted artificial companions for selected objects at separations of 10 AU and 6 AU with roughly equal brightness. Companions at 10 AU were reliably detected, by visually inspecting the image before and after PSF subtraction. They also cause clearly enhanced scatter after PSF subtraction. Thus, we are confident that our companion search is complete down to 10 AU for roughly equal mass systems. At 6 AU, we can still recover artificial companions around the brightest of our targets, but for the fainter ones both the visual inspection and the noise analysis fail. We conclude that our companion search is probably not complete for separations < 10 AU. For the brightest ~ 5 objects, however, we can safely exclude the existence of roughly equal mass companions down to separations of 6 AU.

3. Results

3.1. Resolved Binaries

We find three resolved binaries in the Cha I sample: ChaHα 2, CHXR 15 and Hn 13 (Fig. 1 and Table 2). The first was suspected to be a binary by Neuhäuser et al. (2002) based on its elongated PSF in *Hubble Space Telescope* images. We are also able to recover the previously known companion to 2M1207 in our images. We do not find companions to any other targets.

Interestingly, ChaHα 2, CHXR 15 and Hn 13 are all at the high mass end of our target sample: all have masses > 0.1 M$_\odot$, clearly above the sub-stellar boundary. Two of the

binaries, ChaHα 2 and Hn 13, have mass ratios close to unity ($q = m_2/m_1 > 0.9$) and are slighthly wider (20AU $< a <$ 30AU) than most binaries found in the field. CHXR 15 stands out more: it has a lower mass ratio ($q = 0.64$) and a wider separation ($\sim$ 50AU).

3.2. Binary Frequency

Fig. 2 shows our detection limits as a function of companion mass (according to Baraffe et al. models) and separation (assuming a distance of 160 pc). The survey is able to detect binaries with mass ratios (q) as low as 0.2 for all but one target at 50 AU, and planetary mass companions at larger separations. Our results suggest that wide VLM systems with ultra low mass companions, such as Oph 1622-2405 (Jayawardhana & Ivanov 2006), are rare. We return to this point in the discussion.

For comparison, we also plot the binaries found by Fischer & Marcy (1992) among field stars with primary masses of 0.1-0.6 $M_\odot$ and by Close et al. (2003), Burgasser et al. (2003) and Siegler et al. (2005) among field VLM objects with 0.05–0.1 $M_\odot$. Our survey would have detected nearly all binaries with >20 AU and $q > 0.6$ in these comparison samples. For our Cha I sample, with primary masses between $\sim$0.02-0.2 $M_\odot$, we find a binary frequency of 11^{+9}_{-6}% in the regime where our survey is sensitive to companions ($a > 20\mathrm{AU}, q > 0.6$).

4. Discussion

Our findings in Cha I are similar to what Kraus et al. (2005, 2006) have reported for VLMOs in Taurus and Upper Scorpius star-forming regions. A recent survey of Taurus by Konopacky et al. (2007) targeting mainly VLM stars has revealed a larger multiplicity fraction of wider systems with lower mass ratios, although the binary frequency is still in statistical agreement with our results[2]. In fact, the four surveys target primaries in the same mass range and have comparable detection limits for companions[3]. Thus, we can combine the results of all four surveys (12 VLM targets in Upper Scorpius, 32 in Taurus and 28 in Chamaeleon I) to arrive at a more statistically significant sample of 72 young VLMOs with an overall resolved binary frequency of 7^{+4}_{-3}%. If we just consider T-associations (Taurus and Chamaeleon I), then the multiplicity fraction is 5^{+5}_{-3}%. In both cases we use $a >$ 8AU and

[2]We are not able to extend the analysis to include the Bouy et al. (2006b) survey in Upper Scorpius because that paper does not list the targets and their properties.

[3]We removed three objects in the Konopacky et al. (2007) sample whose masses are greater than 0.15 $M_\odot$.

$q > 0.8$ as our sensitivity limit.

We can now compare the binary properties of young VLMOs with other populations of interest, such as field VLMOs and young stars, to explore possible variations with mass and/or age. We used a Fisher "exact" statistical test for comparing samples of binomial distributions, as detailed in Appendix B of Brandeker et al. (2006). The results are given in Table 3, where "likelihood" refers to the probability that the multiplicity frequencies of the two samples are the same.

4.1. Mass Dependance of Binarity

In order to explore the dependence of the binary frequency on mass we statistically compare several samples spanning different mass bins. As shown in Table 3 and Fig. 4, we constrain the q and separation range as appropriate to ensure that the two samples being compared have the same sensitivity limits for companions. We ensure that samples that are compared are of similar age by only comparing binaries from young associations (Cha I, Taurus and Upper Scorpius). In addition we also address the potential concern about the environmental effects by performing every comparison with and without the 12 targets in Upper Scorpius as it is the only higher density association that contributes binaries to our combined sample. We find that our conclusions are not affected by inclusion of these additional binaries.

We start by dividing the young VLMOs themselves into two groups, following Kraus et al. (2006): one with primary masses less than 0.07 $M_{\odot}$ and the other with primary masses greater than 0.07 $M_{\odot}$. All eight resolved VLMO binaries within the sensitivity limits (Fig. 4A) are in the higher mass bin. The likelihood of the two mass bins having the same binary frequnecy if only T-associations are compared is low ($\sim$ 8%), but not insignificant. If we increase the sample size by adding the Upper Scorpius members, 6 to the lower and 6 to the higher mass bin, the likelihood that the two mass bins have the same binary distribution becomes even lower ($\sim$ 2%). In addition, we also note that 4 systems that are outside of the sensitivity range fall in the higher mass bin and thus further reinforce our point. We can also compare the young VLMO sample with young stars ($\sim$0.57-1.40 $M_{\odot}$) in Taurus and Cha I surveyed by Ghez et al. (1993, 1997) in the sensitivity regime outlined in Fig. 4B. The result (likelihood of $\sim$ 1% and $\sim$ 2% if we include or exlude the Upper Scorpius sample respectively; Table 3) bolsters the case for a decreasing wide binary frequency with mass.

What could account for this observed trend? One possibility is that less massive, and therefore fainter, primaries will have even fainter companions that might not be detectable

by surveys. However, all of the samples presented here are sensitive to mass ratios of $q \geq 0.5$ at separations greater than 30AU and even lower mass ratios at wider separations (Fig 2. and Fig 4.) for the young VLMO sample, allowing us to rule out such a bias. Another possibility is that binary separations (i.e., system size) decreases with mass below our detection limits. A radial velocity survey of Cha I VLMOs finds only one candidate companion (Joergens 2006) at $\lesssim$0.1 AU among 10 targets while Basri & Reiners (2006) find a spectroscopic binary fraction of $\sim$11% in the 0-6 AU separation range among field VLMOs. Imaging surveys of field VLMOs (eg., Close et al. 2003, Siegler et al. 2005), which have typical sensitivities of $q \sim 0.85$ at 3AU, also do not reveal a significant number of companions closer to the primaries. Thus, it appears unlikely that a decrease in separations is the primary reason for the observed drop in multiplicity in the VLM regime. Instead, we conclude that the binary frequency most likely decreases with mass.

4.2. Age Dependance of Binarity

We investigate whether binarity in the VLM regime depends on age by comparing the young VLMO sample with the late M and early L field dwarfs surveyed by Close et al. (2003). They found three nearly equal mass ($q > 0.85$) pairs wider than $\sim$7.5 AU among 85 targets in the $\sim$0.05-0.1 $M_{\odot}$ mass range, resulting in a binary fraction of 4^{+6}_{-4}%, which is in good agreement with that for young VLMOs suggesting that binarity in the VLM regime does not depend strongly on age between a few Myr and several Gyr. One concern is that environments from which these two samples are drawn may be different. The young VLMO sample comes from low density T-associations (and OB-associations if we choose to include Upper Scorpius), while most of the field objects probably formed in higher density clusters. Thus one can argue that the multiplicity fraction we see today in the surveyed SFRs might decrease over time below that seen in the field. It is unlikely, however, that this will happen because the field VLMOs have survived more dynamically active environments.

We also examine the stability of VLM binaries by calculating their binding energies in comparison to those of other binary populations. Fig. 3 shows that even though there is significant overlap of young and field VLM binaries on the binding energy vs. separation plot, young unbound associations also have a significant population of wider binaries. As this is the population that might be disrupted by dynamical encounters, exploration of stability of such systems is important. Regarding this problem, we note that a number of field star systems (those in the boxed area of the figure) are more fragile than the young VLM binaries, even though the former have evolved dynamically already. This is all the more surprising if one considers the fact that these field systems were most likely born in higher density regions

where dynamical evolution would have had a more profound effect. Therefore, it is unlikely that the "harder" VLM binaries, would be disrupted, again supporting the conclusion that age is not a major factor affecting binarity in the VLM regime, at least when one considers OB and T associations[4]

Weakly bound binaries can be disrupted by gravitational perturbations from both stellar encounters and giant molecular clouds, as discussed by Weinberg et al. (1987). Burgasser et al. (2003) applied the formalism of Weinberg et al. (1987) to the BD regime, and found that a pair of $0.05\,M_{\odot}$ BDs separated by 10 AU would be completely impervious to disruption by stellar encounters in the field. Scaling the result of Burgasser et al. (2003) to the most weakly bound system in our combined young VLMO sample, with a total mass of $0.16\,M_{\odot}$ and a separation of 100 AU, we get expected disruption timescales from field stars that are on the order of 600 Gyr, more than 10^5 times older than the age of the systems. These estimates are based on field star densities of $n_* = 0.05\,\mathrm{pc}^{-3}$ (Bahcall & Soneira 1980), which is a critical parameter, as the disruption timescale $\tau \propto n_*^{-1}$. But even assuming a stellar density as high as $n_* = 200\,\mathrm{pc}^{-3}$, corresponding to the outer regions of the Orion Nebula Cluster (Köhler et al. 2006), the disruption timescale would be 150 Myr, two orders of magnitude longer than the present age of the system. This estimate suggests that encounters with other stars do not disrupt even the most weakly bound systems in our sample, either in their birth environments (i.e., in OB or T associations) or later as the stellar densities drop to match that in the field. Since perturbations from giant molecular clouds are insignificant in comparison to stellar encounters (Burgasser et al. 2003), the VLM binaries in our sample are likely to survive almost indefinitely.

4.3. Frequency of Ultra Low Mass Companions

In recent years, several VLM systems that appear to diverge from established trends have been reported. In particular very wide systems such as Oph162225-240515 with ultra low mass companions stand out from field VLM systems whose separation tends to decrease with mass. Because the presence of such systems imposes additional constraints on formation mechanisms, it is important to determine their frequency. Fig. 5 shows that our survey is sensitive to nearly planetary mass companions (down to $9\mathrm{M_J}$) around 23 targets in the Cha I sample at separations greater than 100AU. In addition, such systems could be detected

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[4]To date, 3 very wide (≥ 220 AU) field VLM systems have been discovered (Billéres et al. 2005; Caballero et al. 2007; Artigau et al. 2007). These are not included in our analysis as they are not part of a defined sample. Nevertheless, their existence shows that at least some very wide VLM binaries could survive their birth environment.

around all 34 targets from the Kraus et al. (2005, 2006) surveys of Upper Scorpius and Taurus. Yet, no ultra low mass companions at wide separations are detected in these three surveys, giving a frequency of no more than 2% and thus confirming their rarity.

Since the typical primary mass of the combined VLMO sample is $110\mathrm{M_J}$, and the imaging surveys are sensitive to $q \sim 0.1$ companions (i.e., secondaries with 9–$15\mathrm{M_J}$) at > 100AU, we can also compare our results to surveys for sub-stellar companions to solar analogs. For example, Metchev & Hillenbrand (2005) targeted 100 F5-K5 primaries to look for brown dwarf companions. Based on a single detection, they derive a sub-stellar companion freqency of at least 1%, and possibly on the order of a few percent. This result is in statistical agreement with the frequency of $q \sim 0.1$ systems around VLM primaries in our combined young sample. Therefore, even though VLM systems with planetary mass companions are rare, the frequency of $q \sim 0.1$ binaries in the VLM regime is no different from that for solar-type stars.

5. Concluding Remarks

Our survey of VLMOs in Chamaeleon I lends additional support to the established trend for a lower binary frequency with decreasing primary mass. By comparing the multiplicity properties of young VLMOs with those of field VLMOs and stars, we conclude that there is likely no evolution of multiplicity after the first few Myr for objects formed in low density regions.

While our survey of Cha I and the surveys of Kraus et al. (2005, 2006) and Konopacky et al. (2007) show that wide VLM systems with ultra-low-mass companions – thought to be a critical challange to the ejection formation mechanism – are infrequent, they also reveal a significant fraction of systems considered wide by the ejection scenario (> 20AU). Seven out of thirteen reported systems have separations wider than 20AU, with three systems separated by more than ~ 50AU. Bate et al. (2005) have recently reported that their simulations can produce binaries wider than the initial 20AU limit, albeit via a different mechanism than the one responsible for the production of tighter pairs (i.e., simultaneous ejection and capture of previously unassociated objects vs. ejection of coupled tight binaries). However, since their hydrodynamic simulations are not followed up with N-body calculations, it is difficult to make a direct comparison; many of the reported simulated binaries are still accreting and likely unstable and the statistics are still somewhat limited; there may also be a spread in the ages of objects in a given SFR. In addition, most simulations model higher density regions, more akin to the Orion Nebula Cluster rather than the diffuse T associations that we and other observers have surveyed mostly. Nevertheless, a successful model for star formation

has to account for observed binary properties in the VLM domain, including the existence of some wide pairs.

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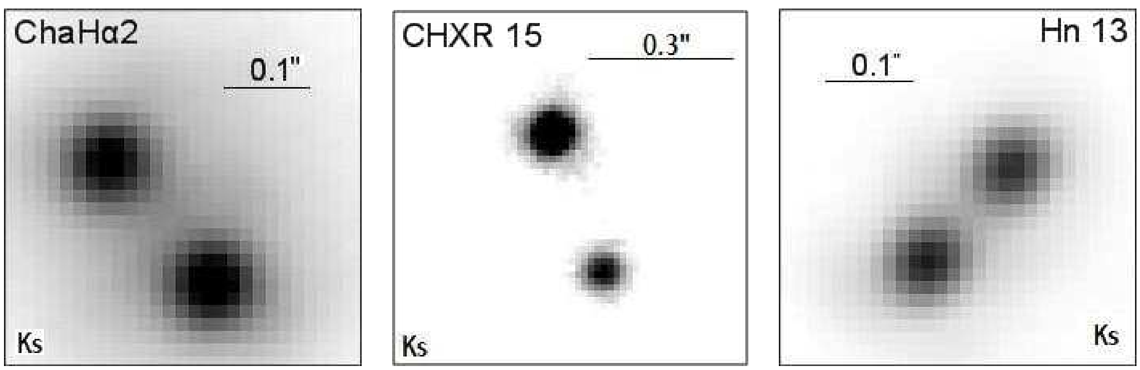

Fig. 1.— Resolved binary systems ChaHα2, CHXR 15 and Hn 13 with separations of $0.164 \pm 0.003''$, $0.305 \pm 0.002''$ and $0.128 \pm 0.002''$ respectively. All images are taken with K_s filter. N is up and E is to the left in all three images.

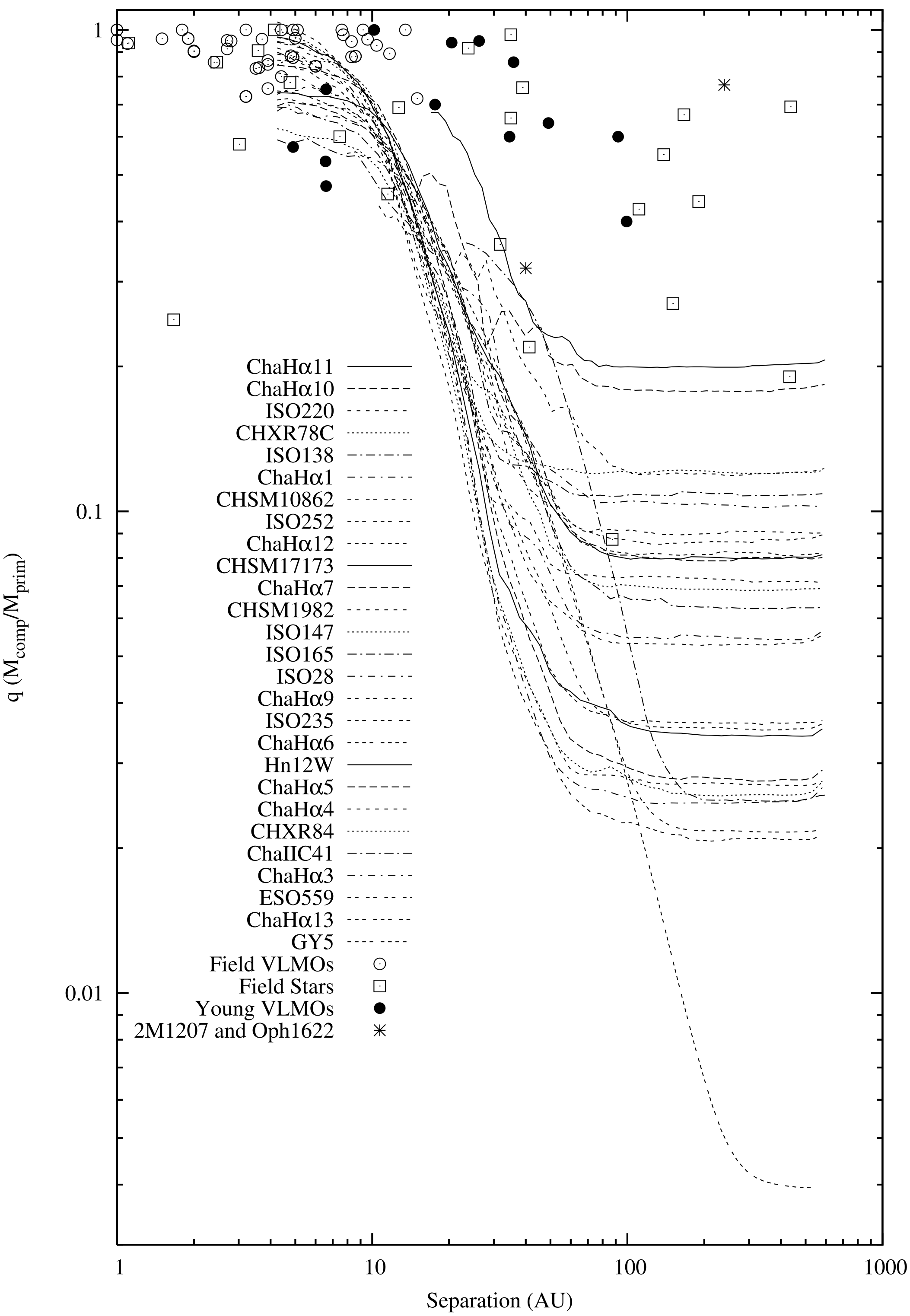

Fig. 2.— Mass sensitivity plot for our survey targets (based on Baraffe et al. 1998, 2003 models). Also included are all resolved young VLMO binaries from Kraus et al. (2005,2006), Konopacky et al. (2007) as well as our Cha I sample, field VLMO binaries (Close et al. (2003), Burgasser et al. (2003), Siegler et al. (2005)) and field stellar binaries (Fischer & Marcy (1992)). For a typical object, we are sensitive to Ks = 16.7 beyond 70AU. (best case Ks = 18.3, worst case Ks = 15.5)

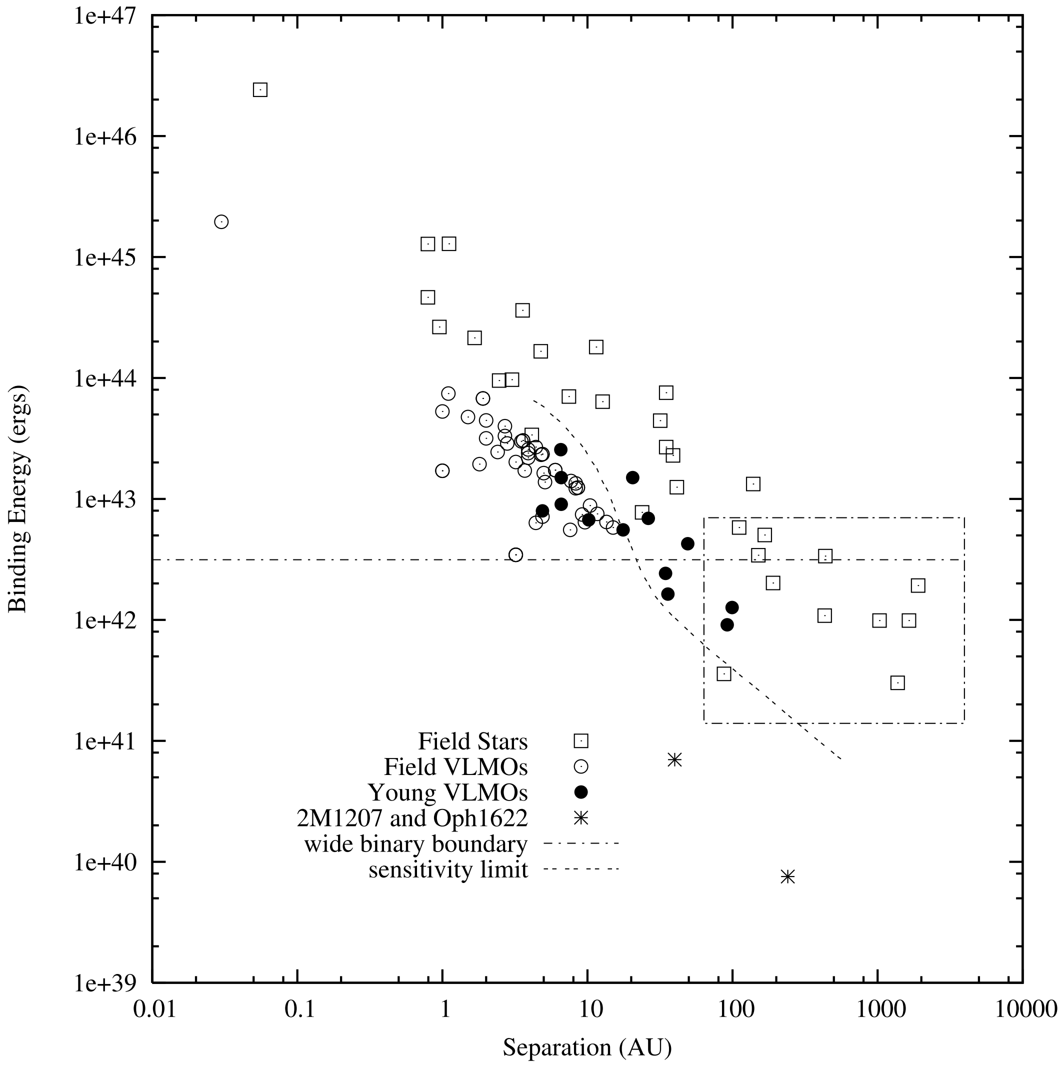

Fig. 3.— Binding energy of young and field VLMOs and field stars. Symbols are the same as those in Fig. 2. We also include the mass dependant definition of wide systems explored by Burgasser et al. (2003), where a wide binary is any system such that $a > 1400 \times \left(\frac{\mathrm{M_{tot}}}{\mathrm{M_\odot}}\right)^2$ AU. Four young VLMOs that are wider than the given limit come from the recent speckle survey of Taurus-Auriga by Konopacky et al. (2007); if these four are unresolved triples –i.e., one component is actually an unresolved equal-brightness binary– then two of them would still be considered wide by the Burgasser et al. (2003) threshold, while if they are unresolved quadruples, all four would satisfy the derived limit.

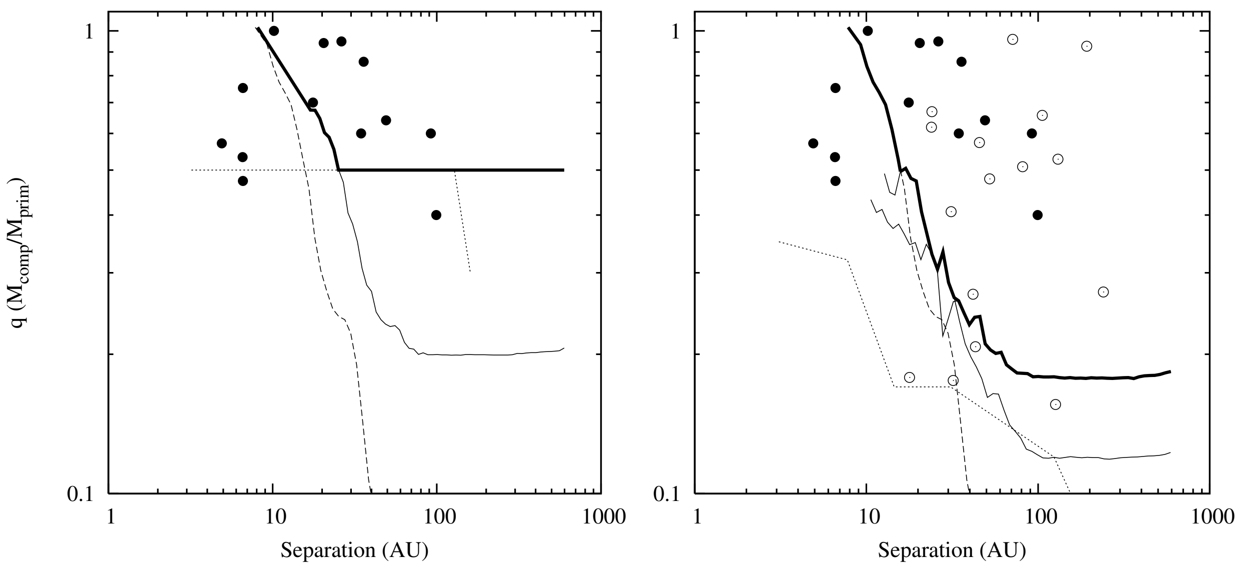

Fig. 4.— Sensitivity limits used for comparisons – (LEFT) between different mass bins in the combined young VLM sample – (RIGHT) between the combined young VLM sample and young stars. We are sensitive to companions up and to the right of the thicker solid line which traces out sensitivity limits from the four surveys of young VLMOs (Kraus et al. (2005,2006), Konopacky et al. (2007) and this survey). Thin solid lines are the sensitivity limits from the Chamaeleon I sample, dotted lines are from the speckle imaging survey of Taurus (Konopacky et al. 2007), while dashed lines are sensitivity limits for the Kraus et al. (2006) Taurus sample, which were determined using the same techniques as those used for the Chamaeleon I sample. Since the Upper Scorpius observations are carried out with the same instument setup (ACS/HST), we assume the sensitivity limits for that sample are similar. In the figure to the right, lower sensitivity limits are achieved by removing two worst offenders (one from the Cha I sample and one from Konopacky et al. (2007) Taurus sample) in order to include as many binaries as possible. The two offenders, especially the one from the Konopacky et al. (2007) survey, are atypical compared to the sample, justifying their removal in order to gain access to a wider parameter space. The solid dots are binaries from the combined young VLM sample while the open circles represent stellar binaries ($0.57 - 1.40\,M_{\odot}$) from Ghez et al. (1993,1997) surveys of Taurus and Chamaeleon I.

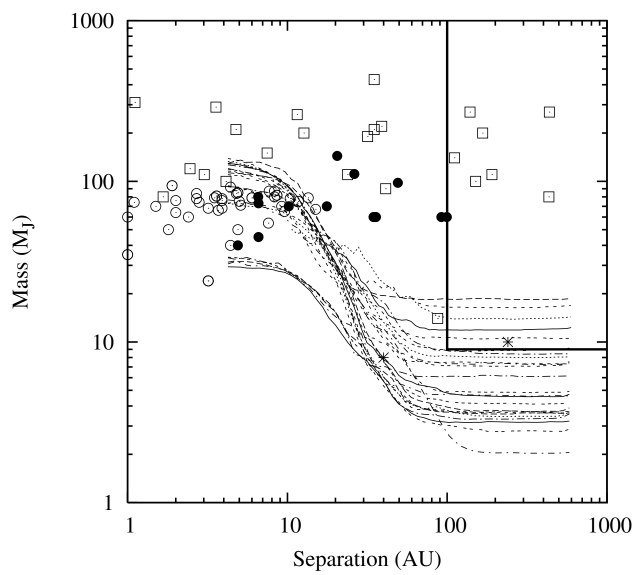

Fig. 5.— Sensitivity limits of our sample in terms of mass. Once again symbols are the same as those in Fig. 2. The thick solid line outlines a region in the top right part of the plot in which we are sensitive down to $9M_J$ companions for most of our sample.

Table 1. VLMOs imaged with NACO/VLT

ID	α(J2000.0)[a]	δ(J2000.0)[a]	K_S[a]	SpT[b]	Mass(M_J)[c]	$T_{\rm eff}$[d]
ChaHα11	11 08 29.27	-77 39 19.8	13.54	M7.25	60	2838
ChaHα10	11 08 24.04	-77 39 30.0	13.24	M6.25	92	2962
ISO138	11 08 18.50	-77 30 40.8	13.04	M6.5	83	2935
CHSM17173	11 10 22.27	-76 25 13.8	12.45	M8	40	2710
ChaHα7	11 07 37.76	-77 35 30.8	12.42	M7.75	45	2752
ChaHα1	11 07 16.69	-77 35 53.3	12.17	M7.75	45	2752
CHSM10862	11 07 46.56	-76 15 17.5	12.33	M5.75	117	3024
ISO147	11 08 26.51	-77 15 55.1	12.35	M5.75	117	3024
CHSM1982	11 04 10.60	-76 12 49.0	12.12	M6	102	2990
ISO252	11 10 41.41	-77 20 48.0	12.27	M6	102	2990
ChaHα12	11 06 38.00	-77 43 09.1	11.81	M6.5	83	2935
ISO220	11 09 53.37	-77 28 36.6	12.23	M5.75	117	3024
ISO28	11 03 41.87	-77 26 52.0	11.69	M5.5	134	3058
ESO559[d]	11 06 26.3	-76 33 42	11.49	M6	102	2990
ChaHα9	11 07 18.61	-77 32 51.7	11.80	M5.5	134	3058
ISO165	11 08 54.97	-76 32 41.1	11.44	M5.5	134	3058
ChaHα2[d,e]	11 07 42.45	-77 33 59.4	10.68	M5.25	153	3091
ChaHα4	11 08 18.96	-77 39 17.0	11.02	M5.5	134	3058
ChaHα3	11 07 52.26	-77 36 57.0	11.10	M5.5	134	3058
ChaHα6	11 08 39.52	-77 34 16.7	11.04	M5.75	117	3024
Hn12W	11 10 28.52	-77 16 59.6	10.78	M5.5	134	3058
CHXR84	11 12 03.27	-76 37 03.4	10.78	M5.5	134	3058
Hn13[e]	11 10 55.97	-76 45 32.6	9.91	M5.75	117	3024
ChaHα13	11 08 17.03	-77 44 11.8	10.67	M5.5	134	3058
ChaHα5	11 08 24.11	-77 41 47.4	10.71	M5.5	134	3058
ISO235	11 10 07.85	-77 27 48.1	11.34	M5.5	134	3058
CHXR78C	11 08 54.22	-77 32 11.6	11.22	M5.25	153	3091
CHXR15[e]	11 05 43.00	-77 26 51.8	10.23	M5.25	153	3091
ChaIIC41[d]	12 59 09.8	-76 51 04	11.4	M5.5	109	3058
GY 5[d]	16 26 21.4	-24 25 59	10.92	M6	81	2990
2MASS1207-3932[d]	12 07 33.4	-39 32 54	11.95	M8	42	2710

[a]2MASS Point Source Catalogue (Cutri et al. 2003), save for ESO559 and GY5, which are from Coméron et al. (2004) and Natta et al. (2002).

[b]Spectral types from Coméron et al. (2004) for ESO559, Natta et al. (2002) for GY 5, Barrado & Jayawardhana (2004) for ChaII C41, Gizis (2002) for 2MASS1207-3932, and Luhman (2004) for all others. Effective temperature is obtained from the spectral types using the Luhman et al. (2003) temperature conversion scale. For the binaries, we assume that the quoted effective temperature is the temperature of the brighter component.

[c]Masses calculated from $T_{\rm eff}$ and evolutionary models of Baraffe et al. (1998,2003) assuming an age of 2 Myr for Cha I, 1 Myr for ρ Oph and Cha II, and 8 Myr for TW Hydrae. We also make a cautionary note: pre-main-sequence mass models are poorly calibrated and are also vulnerable to the age spread of Cha I, resulting in significant uncertainties.

[d]Object observed during the preliminary survey from May to September 2005.

[e]Detected binaries. Masses of the primaries are listed.

Table 2. Resolved Binaries

ID	Sep($''$)[b]	PA($^\circ$)[a,b]	Band	m_A[b]	m_B	mass ratio[c]
ChaHα2	0.164 ± 0.003	40.6 ± 1.9	Ks	11.39 ± 0.05	11.47 ± 0.06	0.94
Hn13	0.128 ± 0.002	318.0 ± 1.9	Ks	10.62 ± 0.04	10.70 ± 0.04	0.95
Hn13	0.128 ± 0.002	318.7 ± 1.9	H	11.11 ± 0.05	11.25 ± 0.05	—
CHXR15	0.305 ± 0.002	200.0 ± 1.4	Ks	10.73 ± 0.05	11.33 ± 0.07	0.64
CHXR15	0.304 ± 0.003	200.0 ± 1.4	H	11.14 ± 0.05	11.67 ± 0.07	—

[a]Position angle is measured from north to east.

[b]Photometry and astrometry measurements (along with uncertainties) of the two components were obtained with the DAOPHOT routine in IRAF. Additionally, there is a 1° systematic uncertainty on the position angle. After measuring the flux ratio of the primary and the secondary, we use it along with the 2MASS catalogue K_s and H magnitudes for the combined flux to determine the magnitudes of each component. We obtain the masses from effective temperatures.

[c]Uncertainties in the mass ratio are dominated by systematics (eg., unresolved higher order multiplicity, intrinsic variability of young VLMOs).

Table 3. Statistical Sample Comparison

# of Binaries/Sample A Size	# of Binaries/Sample B Size	Likelihood
Lower Mass Young VLMOs ($< 0.07\,M_\odot$) **& Higher Mass Young VLMOs** ($0.07 - 0.15\,M_\odot$)		
0/27,0/21	8/45,6/39	0.02,0.08
Young VLMOs ($0.04 - 0.15\,M_\odot$) **& Young Stars** ($0.57 - 1.40\,M_\odot$)		
9/70,7/58	12/34,12/34	0.02,0.01

Note. — Entries listed in each column represent samples and statistical comparisons with and without Upper Scorpius members.